

Hadronic Physics

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Abstract. A selection of studies highlighting different manifestations of the strong interaction are presented. Many new results have become available this summer in the regimes of discovery, systematic survey, and precision measurements of bound quark states.

1. Introduction

The investigation of bound states of quarks provides insight into the strong force, by which they are held together. Doing so with different kinds of hadrons allows one to study different manifestations of QCD. Especially at low scales, however, modeling such phenomena is challenging.

Quark models predict systems of states for different quark configurations that can be confronted with experimental data. While several possible configurations would in principle be useful to study, including bound gluon-only states, the objects that lend themselves to this exercise more easily are mesons and baryons. Beyond these two-quark or three-quark systems predicted within this framework, other bound configurations can exist that have quantum numbers not predicted in the nonrelativistic quark model (“exotics”) or have four or five quark constituents.

This summary focuses on results that were new this summer. A selection of topics will be presented, illustrating ways to study the effects of strong interaction from low to high energies. This covers baryons and mesons. For a summary on pentaquarks, I refer the interested reader to Ref. [1]. The analyses divide into three categories: (1) new phenomena, (2) systematic surveys and complementary approaches to verify new phenomena, (3) precision measurements.

2. Two heavy quarks

Heavy quarkonium, bound states such as $c\bar{c}$ or $b\bar{b}$, are an ideal laboratory for studying the strong potential as the masses and widths of states are directly related to the strong force holding them together, mediated by gluons. From a researcher’s standpoint, this is the same scenario as positronium, where the electron and positron are held together by the electric force, mediated by photons. However, the energy scale is vastly different for hadrons. Bottomonium, with heavier constituents of about 5 GeV than charmonium, can be treated as non-relativistic. On the other hand, charmonium, with the lowest-lying state at just below 3 GeV, affords the opportunity to study the importance of relativistic corrections. I will list examples for spectroscopy, decay, and searches for quarkonium states. While substantial bottomonium samples on the $\Upsilon(1, 2, 3S)$ exist (direct production or radiative return from higher energies), most progress this summer was made for charmonium.

2.1. Below open flavor threshold

All charmonium states below open-flavor threshold have been observed [2]. Large samples exist for the J/ψ and $\psi(2S)$, which are well-studied. The masses and widths have been determined at high accuracy. The focus is now on comparing the two states, identifying rare decays, and investigating the resonant substructure in multibody states. As for open charm, this provides information on the intermediate states produced and gives insight into the decay dynamics. A scan of the $\psi(2S)$ by E385 [3] led to the current most precise results of $\Gamma(\psi(2S)) = (290 \pm 25 \pm 4) \text{ keV}$ and $\Gamma(\psi(2S) \rightarrow e^+e^-) \times \mathcal{B}(\psi(2S) \rightarrow p\bar{p}) = (0.579 \pm 0.038 \pm 0.036) \text{ keV}$. The process used was $p\bar{p} \rightarrow \psi(2S)$ with $\psi(2S) \rightarrow e^+e^-$ or $\psi(2S) \rightarrow XJ/\psi \rightarrow Xe^+e^-$. The analysis makes use of the small beam energy spread, which is comparable to the structure investigated as opposed to the $\sim \text{MeV}$ range to which e^+e^- machines are limited.

The χ_{cJ} states can be studied using the reaction $\psi(2S) \rightarrow \gamma\chi_{cJ}$, where they are produced at a branching ratio of a little under 10% each. Once the transition photon is identified, the χ_{cJ} are easy to handle experimentally. Given the $\psi(2S)$ sample sizes, this implies that the χ_{cJ} data are not far behind the $\psi(2S)$ in statistical power, and similar studies as for the $\psi(2S)$ are being conducted. The transition rates are affected by relativistic corrections, and thus measuring them accurately is important to guide theory. The $\eta_c(1S, 2S)$ and the h_c are less well known, and studies to learn more about their properties and decays are under way.

CLEO-c presented a study of decays $\chi_{cJ} \rightarrow h^+h^-h^0\pi^0$ [4]. Branching fractions for the final states $\pi^+\pi^-\pi^0\pi^0$ (and resonant sub-mode $\rho^\pm\pi^\mp\pi^0$), $K^+K^-\pi^0\pi^0$ (and resonant sub-mode $K^*K\pi$), $p\bar{p}\pi^0\pi^0$, $K^+K^-\eta\pi^0$, and $K^\pm\pi^\mp K^0\pi^0$, were determined. Most of these are first measurements. Isospin relations in the submodes $\rho^\pm\pi^\mp\pi^0$ and $K^*K\pi$ are found to be consistent with expectations.

BES investigated the decay $J/\psi \rightarrow K^+K^-\pi^0$ [5]. The distribution of $M^2(K^+\pi^0)$ vs. $M^2(K^-\pi^0)$ shows the expected bands of the $K^*(892)$ and the $K^*(1410)$. The necessary fit components to get a reasonable description of the data are $K^*(892)$, $K^*(1410)$, $\rho(1700)$, a non-resonant contribution, and a Breit-Wigner with a mass-dependent width function for a broad enhancement in $M(K^+K^-)$ around 1.6 GeV, which does not match any known particles. It is not possible to use ρ excitations to describe the observed distribution. C -parity conservation implies that this state should have odd J and $PC = --$; the fit prefers 1^{--} . The pole position, which is chosen instead of Breit-Wigner-like parameters to quote a result, as determined by the fit is $(1576_{-55}^{+49+98}) \text{ MeV} - i(409_{-12}^{+11+32}) \text{ MeV}$; a product branching fraction $\mathcal{B}(J/\psi \rightarrow X\pi^0) \times \mathcal{B}(X \rightarrow K^+K^-) = (8.5 \pm 0.6_{-3.6}^{+2.7}) \times 10^{-4}$ is found. Future studies will focus on a search for the same phenomenon in isospin-related final states to clarify the nature of this state.

Studies of charmonium production in B decay aim at gaining insight into the production mechanism and variations among different $c\bar{c}$ states. The η_c , J/ψ and χ_{c1} (and excitations) along with a K or K^* can be created through $b \rightarrow c\bar{c}s$, but production of h_c , χ_{c0} , and χ_{c2} must involve different mechanisms. A prediction [6] states that they can be produced as copiously as χ_{c1} (the branching fractions $\mathcal{B}(B \rightarrow \chi_{c1}K^{(*)})$ are of order 10^{-4}). This holds for the χ_{c0} , at $\mathcal{B}(B^+ \rightarrow \chi_{c0}K^+) = (1.4_{-0.19}^{+0.23}) \times 10^{-4}$, but the current upper limits for h_c (from $B^+ \rightarrow h_cK^+$) and χ_{c2} are an order of magnitude lower. BaBar presented preliminary results for B^+ and B^0 decay to final states with $\eta_c \rightarrow K_S K^+ \pi^-$, $K^+ K^- \pi^0$ and $h_c \rightarrow \gamma \eta_c$ [7]: $\mathcal{B}(B^0 \rightarrow \eta_c K^{*0}) = (6.1 \pm 1.4) \times 10^{-4}$ (uncertainty improved by 50%), $\mathcal{B}(B^+ \rightarrow h_c K^+) \times \mathcal{B}(h_c \rightarrow \gamma \eta_c) < 5.2 \times 10^{-5}$ at 90% CL (in agreement with Belle), $\mathcal{B}(B^0 \rightarrow h_c K^{*0}) \times \mathcal{B}(h_c \rightarrow \gamma \eta_c) < 2.4 \times 10^{-4}$ at 90% CL (first limit). The branching fraction $\mathcal{B}(h_c \rightarrow \gamma \eta_c)$ is not known. The current level of sensitivity does not yet allow a firm conclusion on the level of suppression of h_c production.

2.2. Above open flavor threshold

Little is known about charmonium states above $D\bar{D}$ threshold. Candidates for the states 3^3S_1 , 2^3D_1 , and 4^3S_1 ($J^{PC} = 1^{--}$) are identified as peaks in the spectrum of the inclusive

hadronic cross-section; their positions and widths match theoretical predictions for those states. Observation of other states not accessible in e^+e^- collisions is possible in B decay, $p\bar{p}$ production, or through a transition from a higher-mass state.

A fit to the R spectrum provides the masses and widths of the $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, but the extraction of these quantities is not without ambiguity. BES, for the first time, attempted to take interference between these broad resonances into account [8]. The parameters determined show substantial variation with respect to a fit without interference.

An interesting question is what the inclusive cross-section is composed of; a question that a fit to the cross-sections measured for exclusive decay samples in data taken in the charm region (CLEO) or with initial state radiation from higher energies (BaBar, Belle) can answer. Belle presented a new study [9] of $D\bar{D}$ and $D\bar{D}\pi$ (not through a D^*) that augmented an earlier publication on $D\bar{D}^*$, D^*D^* [10]. Summed up, the features of the inclusive spectrum from BES are reproduced, aside from a shift due to the smooth contribution from uds continuum. The components not present in such a comparison are expected to be of comparatively low cross-section: charmonium production, D_s production, charm baryons, other $D\bar{D}n\pi$ (non-resonant), $D\bar{D}^*\pi$ (CLEO [11]).

The distribution of $D\pi$ in the $D\bar{D}\pi$ sample shows a preference for $M(D^-\pi^+)$ near the $D_2^*(2460)$. Selecting events of this type, namely $DD_2^*(2460)$, and plotting their invariant mass, a peak of 14σ statistical significance at the $\psi(4415)$ is found at $m = (4.411 \pm 0.007(\text{stat}))$ MeV, $\Gamma = (77 \pm 20(\text{stat}))$ MeV. The mass and width extracted match those from the inclusive BES analysis [8], $m = (4.4152 \pm 0.0075(\text{stat}))$ MeV and $\Gamma = (73.3 \pm 21.2(\text{stat}))$ MeV. The $D\bar{D}\pi$ events where $M(D^-\pi^+)$ is outside the $D_2^*(2460)$ region are consistent with background from sidebands below 4.6 GeV and show a slow rise thereafter, consistent with CLEO-c's findings [11], where $D\bar{D}\pi$ is not observed at energies below 4.26 GeV.

No other exclusive decay branching fractions have been measured for charmonium states above the $\psi(3770)$ (only upper limits exist) [2].

The properties such as production / decay patterns or masses / widths of some other states have been found to resemble those of expected charmonium states. In most cases, it is difficult to come up with an unambiguous assignment for them based on the experimental evidence available to date. Examples follow.

Belle analyzed their ISR data for the decay $e^+e^- \rightarrow \gamma(\pi^+\pi^-J/\psi)$ [12], in order to improve knowledge of the $Y(4260)$. This state has been seen before by BaBar, Belle, and CLEO, but thus far only been fit to a single Breit-Wigner resonance. Belle attempted a fit using two Breit-Wigner shapes that interfere so as to obtain a better description in particular of the low-side tail of the $Y(4260)$. Due to a mathematical ambiguity, two solutions are found that yield an identical description of the data, have the same values for masses and width, but result in substantially different product of couplings of the $Y(4260)$ and the $X(4008)$ (the resonance associated with the low-side Breit-Wigner) to the initial and final state, $\mathcal{B}(X \rightarrow J/\psi\pi^+\pi^-) \times \Gamma_{ee}$. The properties of the $Y(4260)$ contribution are consistent with those published earlier by BaBar and CLEO.

The distribution of $m(\pi^+\pi^-)$ favors higher values for events taken from $m(\pi^+\pi^-J/\psi)$ near the $Y(4260)$, matching the observation by other experiments, but is consistent with phase space for events above or below the $Y(4260)$ peak region.

Belle also searched for $e^+e^- \rightarrow \gamma(\pi^+\pi^-\psi(2S))$ [13]. Belle confirmed the BaBar observation of a peak at $m(\pi^+\pi^-\psi(2S)) = 4.35$ MeV, with similar parameters, but a second peak at 4.66 GeV is found: $m = (4664 \pm 11 \pm 5)$ MeV, $\Gamma = (48 \pm 15 \pm 3)$ MeV. The distribution of $m(\pi^+\pi^-)$ is inconsistent with phase-space decay for the lower-mass peak, but shifted towards higher values. In the case of the second peak, the distribution strongly favors high values; the $m(\pi^+\pi^-)$ distribution is suggestive of the $f_0(980)$.

Another as yet unexplained state is the $X(3940)$, observed by Belle in $e^+e^- \rightarrow J/\psi D^{(*)}D^{(*)}$ as a peak in the $m(D^*D)$ distribution of events recoiling against the J/ψ . More Belle data

confirm [16] the existence of this state, with consistent parameters but improved significance. A question that needs to be addressed in order to facilitate a quantum number assignment and placement in the charmonium system is to which degree this state decays to $D\bar{D}$, and to also check for structure in $D^*\bar{D}^*$ ($m(X(3940))$ is well below $2m(D^*)$ though). The $m(D\bar{D})$ spectrum shows no peak at 3.94 GeV above background, but a broad threshold enhancement. Before a limit for $\mathcal{B}(X(3940) \rightarrow D\bar{D})$ can be set, this will have to be understood. In $m(D^*D^*)$, a broad peak of more than five sigma statistical significance is observed, which is identified as a new particle $X(4160)$ and fit with a Breit-Wigner function. While the parameters for the $X(4160)$ differ from those of the $X(3940)$, there is some overlap due to the large widths of both.

BaBar confirmed Belle's observation [14] of the $Y(3940)$ in $B \rightarrow K(\omega J/\psi)$, with substantially improved statistical and systematic uncertainties [15]. The BaBar mass and width are substantially, but not significantly (-1.7σ and -1.5σ , respectively), lower than Belle's.

3. One heavy quark

The theoretical treatment of particles with one heavy and one light quark differs in that the two degrees of freedom are decoupled and the heavy quark can be treated as stationary. Similar guidelines as in quarkonium apply, and it is important to aim for a complete picture in which the existence and properties of the expected states are searched for.

Belle investigated angular distributions of the decay $D_{s1}(2536)^+ \rightarrow D^{*+}K_S$ [17], a state which has been observed before: $J^P = 1^+$, total angular momentum of the light degrees of freedom $j = 3/2$, known decays $D^{*+}K_S$, $D^{*0}K^+$, $D_s^+\pi^+\pi^-$. A new mode was observed, $D_{s1} \rightarrow D^+\pi^-K^+$ (but not through D^{*0}), and the ratio $\mathcal{B}(D_{s1}^+ \rightarrow D^+\pi^-K^+)/\mathcal{B}(D_{s1}^+ \rightarrow D^{*+}K^0)$ is found to be $(3.17 \pm 0.17 \pm 0.36)\%$ (preliminary). The angular study of $D_{s1} \rightarrow D^*K_S$ provides a handle on the mixing between two $J^P = 1^+$ states D_{s1} and $D_{sJ}(2460)$. Within the Heavy Quark Symmetry the state with $j = 3/2$ (which is naively expected to be D_{s1}) decays to D^*K_S in a pure D -wave, while the one with $j = 1/2$ does so in an S -wave. Mixing between the two can result in an S -wave component in $D_{s1}(2536)$ decay. This contribution to the total width is determined from a partial wave analysis and found to be substantial: $\Gamma_{S\text{-wave}}/\Gamma_{\text{total}} = 0.72 \pm 0.05$ (preliminary).

Much more progress has been made in meson and baryon spectroscopy [18, 19]. BaBar conducted a systematic search for charm baryons decaying to final states Λ_c^+ plus K_S , K^- , $K^-\pi^+$, $K_S\pi^-$, $K_S\pi^+\pi^0$, $K^-\pi^+\pi^-$ [19]. Their preliminary results confirm the states $\Xi_c(2980)^+$, $\Xi_c(3077)^+$, and $\Xi_c(3077)^0$, improve the mass and width measurements of $\Xi_c(2980)^+$, and discover two new states: $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$. They are only observed by their decays to $\Sigma_c(2455)^{++}K$ and $\Sigma_c(2520)^{++}K$, implying that contrary to the other cases the c and the s quark in the parent particle separate.

4. Zero heavy quarks

Theoretical treatment of mesons with only light quarks demands non-perturbative methods. Guidance in these soft processes comes from scattering experiments as well as studies of decays.

KLOE investigated the decay $\phi \rightarrow \pi^0\pi^0\gamma$ [20] to help shed light on the nature of the $f_0(980)$. The analysis complements that of other final states such as $\pi^+\pi^-\gamma$ or $\eta\pi^0\gamma$ that are aimed at the $f_0(980)$ and $a_0(980)$, broad scalar resonances that appear as intermediate states also in many heavy-quark decays. Producing them in ϕ decay makes it possible to study them close to their production threshold. The Dalitz plot $m(\pi^0\gamma)^2$ vs. $m(\pi^0\pi^0)$ is fit with two different models that test for the existence of an intermediate kaon loop ($\phi \rightarrow \gamma K^+K^- \rightarrow f_0(980) \rightarrow \pi^0\pi^0$) or a pointlike coupling ($\phi \rightarrow f_0(980) \rightarrow \pi^0\pi^0$). Both models fit the data reasonably well, couplings are measured, and the product branching ratio is determined.

The $\eta\text{-}\eta'$ system is often parametrized by a mixture of two components: $|u\bar{u} + d\bar{d}\rangle/\sqrt{2}$ and $|s\bar{s}\rangle$. The mixing angle can be determined for instance from the ratio $\mathcal{B}(\phi \rightarrow \eta'\gamma)/\mathcal{B}(\phi \rightarrow \eta\gamma)$. Under the assumption that no gluonium contributes, KLOE determines the mixing angle in

the quark-flavor basis to be $\phi_P = (41.4 \pm 0.3 \pm 0.7 \pm 0.6)^\circ$ [22], the most precise result to date. States of pure glue content are predicted to exist at higher energies, yet low enough that they may mix with the η' . Allowing for such a component in the η' introduces another mixing angle to quantify the gluonium contribution. Within this parametrization and combined with other such ratios from external input, an improved agreement between SU(3) predictions and the observed branching fraction results is achieved if a gluonium component is allowed. The squared amplitude coefficient for this component is determined to be $(14 \pm 4)\%$. The result for θ_P is not very sensitive to this change in parametrization. The range of values for θ_P determined here is consistent with determinations in the octet-singlet basis in other experiments.

Searches for decay to undetectable final states are not only relevant in the perpetual quest for new physics, but also so as to ensure that the total decay width may be approximated by sum of all observed decays. BES searched for the decay $\eta' \rightarrow$ undetectable final states, where the η' is produced in the reaction $J/\psi \rightarrow \phi\eta'$ [23]. The ϕ as a narrow resonance is readily identified via its decay into a charged kaon pair, and kinematics constrain the recoiling η' to a narrow region in the missing momentum. No signal is seen; an upper limit is placed on the decay of η' to invisible final states relative to decay into two photons, which translate into absolute branching fractions of $\eta, \eta' \rightarrow$ invisible of 7×10^{-4} and 2×10^{-3} , respectively. For comparison, similar studies for the $\Upsilon(1S)$ led to a limit of 0.3% [2].

CLEO used the transition $\psi(2S) \rightarrow \eta J/\psi$ with $J/\psi \rightarrow \ell^+\ell^-$ to study the η meson. Branching fractions and ratios thereof [24] were determined for $\eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma$, and $e^+e^-\gamma$, a first for such a suite of modes within the same experiment. These branching fractions are of order 1% or larger; the ones not covered are at least an order of magnitude lower, and their sum is estimated to amount to no more than 0.2%. Deviations from previous determinations were observed for $\pi^+\pi^-\gamma$ and $e^+e^-\gamma$ at the level of three standard deviations. The kinematic conditions allowed CLEO to measure the η mass [25] through a fit of the invariant mass of the decay products (except $e^+e^-\gamma$, which has too few events). The precision achieved is comparable with that of dedicated experiments. CLEO, agreeing with NA48 and KLOE, indicates a recent GEM result as an outlier.

KLOE's high-statistics study [26] of $\eta \rightarrow \pi^+\pi^-\pi^0$ aims at testing the degree to which lowest-order current algebra is able to describe the decay dynamics. If this is accurate, then the decay amplitude can be used to extract a measurement of the u - d quark mass difference in a simple way. A fit to the Dalitz plot is performed up to third order in kinematic quantities. While coefficients that would indicate charge violation are found to be zero (current best limits), in line with expectation, comparing a relationship between other components reveals that lowest-order current algebra is not sufficient.

The decay rate for $K^+ \rightarrow \pi^+\pi^0\pi^0$ can be used to understand final state interactions, undertaken by NA48 [27]. In a simplified picture where the production of the three pions is instantaneous, the $m(\pi^0\pi^0)^2$ distribution shows a rapid rise at the kinematic limit and then quickly changes slope to an almost linear behavior. Experiment shows the rise to be slower than expected and a distinct change in behavior ("cusp") at $\pi^+\pi^-$ production threshold. Below this point, there is a depletion of events relative to the expectation. This is due to the fact that the amplitude for the direct decay $K^+ \rightarrow \pi^+\pi^0\pi^0$ interferes with rescattering amplitudes, for example the one-loop process $K^+ \rightarrow \pi^+(\pi^+\pi^-) \rightarrow \pi^+\pi^0\pi^0$. The area above the cusp allows to observe sub-leading effects. NA48's high-precision data (updated, preliminary) allow to explore the sensitivity of the Dalitz plot to the scattering lengths a_0 and a_2 , for which theoretical predictions from chiral perturbation theory exist. The measured values are consistent with those obtained in $K \rightarrow \pi^+\pi^-e\nu$ and pionium lifetime measurements.

A clean way to explore final state interactions close to threshold is $K \rightarrow \pi^+\pi^-e\nu$, with new work by NA48 [27]. The fit to describe the amplitude uses a model-independent approach to measure form factor coefficients, achieving a new level of sensitivity, and allows to extract a_0

and a_2 in an independent manner (albeit with further theoretical input). The new preliminary results are consistent with an earlier publication on a partial sample. For both the $K \rightarrow \pi^+ \pi^- e \nu$ and $K^+ \rightarrow \pi^+ \pi^0 \pi^0$ decays, the evaluation of isospin breaking corrections are ongoing theoretical efforts.

5. Summary

From highest to lowest energies, a range of phenomena induced by the strong interaction are being explored. All are important in order to arrive at a complete picture of QCD. Much headway has been made in terms of precision measurements, while many observations remain unexplained.

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